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ASSOCIATION D'OCÉANOGRAPHIE PHYSIQUE

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PUBLICATION SCIENTIFIQUE No 4

PHIL E. CHURCH

TEMPERATURES of the WESTERN NORTH ATLANTIC from THERMOGRAPH RECORDS

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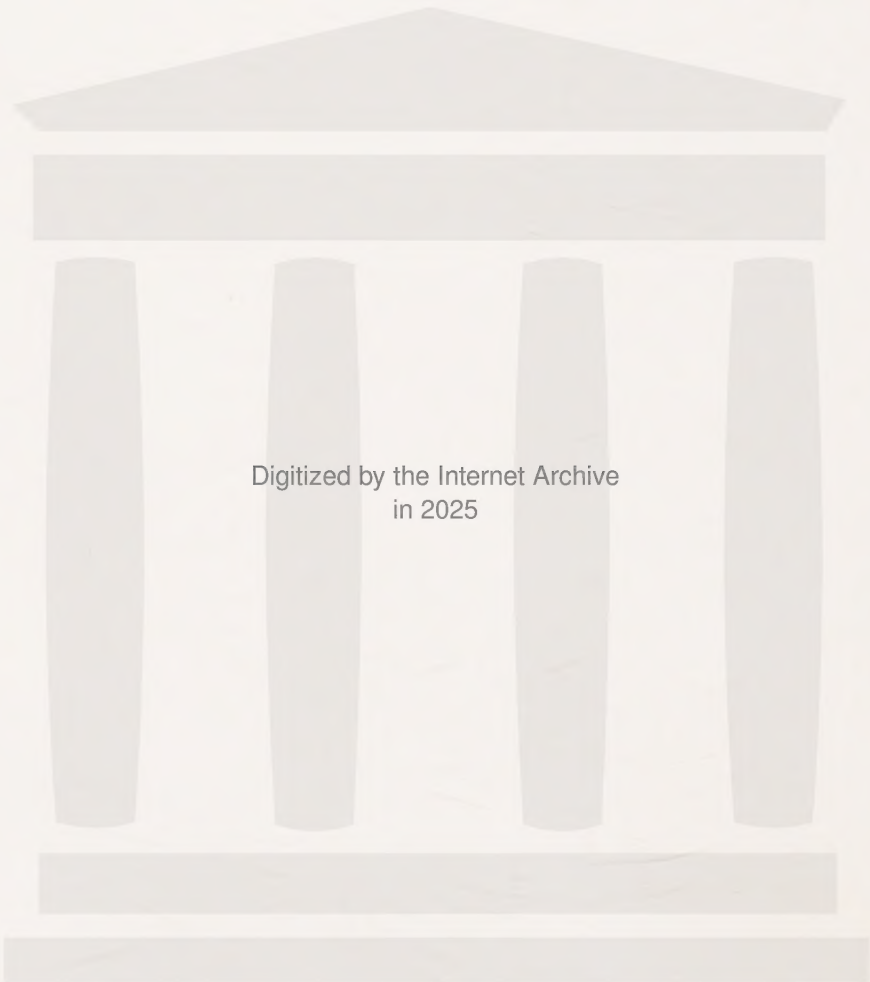
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The Association issues two series of publications, viz. "Publications Scientifiques" and "Procès-Verbaux."

The following numbers have already appeared:—

PUBLICATIONS SCIENTIFIQUES.

No. 1. S. F. GRACE:
I. Historical review of dynamical explanations of tides in non-elongated enclosed seas and lakes.
II. Historical review of dynamical explanations of the tides of the Mediterranean, the Baltic Sea, the Gulf of Mexico, and the Arctic Ocean. (1931.)

No. 2. Tidal Bibliography (Third instalment). (1932.)

No. 3. Bibliography on tides and certain kindred matters (Fourth instalment). (1936.)

PROCÈS-VERBAUX.

No. 1. Cinquième Assemblée Générale réunie à Lisbonne Septembre 1933. (1934.)

These publications form a continuation of the "Bulletins de la Section d'Océanographie de l'Union Géodésique et Géophysique Internationale," of which there were 17 numbers, No. 1 being issued in 1921 and No. 17 in 1931.

Temperatures of the Western North Atlantic from Thermograph Records *

By

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Commercial vessels with thermographs have made many frequent and rapid crossings of the western part of the North Atlantic from which important surface temperature data have been derived.‡ The first instrument was installed on the S.S. *Coamo*, and has been in continuous operation since 1926. Others were placed in operation later. By November 1928 the number of thermographs carried on vessels provided sufficient data to construct synoptic charts, each of which was made from data taken within a week or, occasionally, ten days. One hundred charts have been constructed from data recorded during the period between November 1928 and December 1933. Approximately twelve hundred thermograms have been studied, and this has extended the period of observation up to the spring of 1935. From the thermograms that have been charted and a study of those not charted, it has been possible to reconstruct

* This study was made under the direction of Dr. H. B. Bigelow, Director of the Woods Hole Oceanographic Institution, and Dr. C. F. Brooks, Director of Blue Hill Observatory, Harvard University. The charts were prepared by Phil E. Church, Keith B. Allan, and E. Monroe Harwood.

† Contribution No. 121 from the Woods Hole Oceanographic Institution.

‡ While this paper was nearing completion, Iselin's (Iselin, 1936) paper on the circulation of the western North Atlantic came off the press. Though these two papers touch the same points in several places, each study has its own set of data, and the subject-matter does not overlap. Iselin's paper treats sub-surface as well as surface conditions from data collected mainly by the *Atlantis*, whereas this paper is concerned only with surface temperatures automatically recorded by vessels running on scheduled trips.

the actual surface temperatures at any time over the western North Atlantic, the changes that occurred from week to week and month to month. Though the period recorded may be considered short, it is probable that the mean temperatures and the annual range, as established by this study, are fairly accurate.

Thirteen thermographs are now operating in eight steamer lanes (see fig. 1). These include (1) Halifax, Boston, Bermuda, and Lesser Antilles ports, and Georgetown (Canadian National S.S. Co.); (2) New York, Cape São Roque, Rio de Janeiro, and Montevideo (São Paulo Tramway, Light, and Power Co., Ltd.); (3) New York to Bermuda (Furness-Bermuda Line); (4) New York to San Juan, P. R. (Puerto Rico Line); (5) New York, Nassau, Miami, and Habana (Munson Line); (6) New York to Habana to Colon (Panama-Pacific Line); (7) Port Tampa to Habana (Peninsula and Occidental Steamship Co.); and (8) Cape São Roque, Trinidad, and New York (São Paulo Tramway, Light, and Power Co., Ltd.).

Up to the beginning of 1931 the vessels plying over Route 1 formerly went from Halifax directly to Bermuda and called at St John, N.B., on the return (route 1 B). Since then they have been rerouted to call at Boston (route 1 A) after leaving Halifax and when returning to Halifax; thus though one important line has been lost an equally valuable data line has been gained.

All these itineraries form a fairly close network of data lines (see fig. 1), particularly in the extra-tropics where surface fluctuations are apt to be rapid. Three lanes within the tropics touch the north coast of South America; one at Cape São Roque, one at Georgetown, and one at Colon. Vessels carrying the thermographs of the São Paulo Tramway, Light, and Power Co., Ltd., bound for New York from Rio de Janeiro, call at Trinidad, thereby producing a data line along the eastern two-thirds of the north coast.

The thermographs (Church, 1932 *a*) are installed with the thermal units exposed to water coming through the intake for the condenser. Though this is not strictly surface water, the intake being from 3 to 8 meters below the surface depending on the vessel and its load, there is little difference between the temperature of the water at that level and the surface (Brooks, 1926; Krummel, 1907). Furthermore, fluctuation from diurnal

heating and nocturnal cooling is practically eliminated at this depth.

Each thermograph is frequently checked against a standard Weather Bureau thermometer by a Weather Bureau official when the vessel is in port at the end or beginning of a voyage. Any error which may creep into the instrument is caught and the thermograph adjusted. Where steamer routes cross and the time interval between vessels is less than a day or two at the point of crossing, or when vessels leave New York within a day, the thermographs may be checked against each other. In only a few instances have they failed to register within ·5 of a degree Centigrade of each other. This checking for accuracy materially aids in establishing that the instrumental errors are well within the limits needed for this study.

Survey of the Temperatures by Sub-areas

A study of the thermograms and the charts show a number of sub-areas of distinct temperature characteristics (see fig. 2). Fixed and exact boundaries cannot be given for each sub-area owing to the mobility of water and the temperature changes during the seasons, but there is a surprising degree of regularity in position of these thermally different surface waters. Furthermore, there is a notable similarity of other physical characteristics in the sub-areas outlined below.

In general, north to south, these sub-areas include: (1) the coastal water; (2) the Slope-water (Harwood and Brooks, 1933; Iselin, 1936); (3) the "cold wall"; (4) the Gulf Stream (Iselin, 1933, 1936); (5) the Central Atlantic water, commonly called the "Sargasso Sea"; and (6) the Northern Equatorial Current. The last named may be further subdivided because of its thermally banded nature.

I. *Coastal Water*

This sub-area includes the water lying over the continental shelf from the Florida Straits to the Gulf of St Lawrence. The seaward limit is definitely marked by the 200-meter contour.

Thermograph records are not suitable for making an accurate study of the surface temperatures of this sub-area

*

because all lanes, except the Boston-Bermuda, focus at New York. Vessels which make Diamond Shoal Light Vessel (off Cape Hatteras) from New York supply a line of data which is of value for showing only the latitudinal distribution of the isotherms. This must be supplemented by data from other sources to show the direction and distribution of the isotherms over the whole sub-area. Fortunately, detailed descriptions of the surface temperatures exist in the papers of Harwood and Brooks (1933), Bigelow (1928, 1933), Parr (1933), Rathbun (1887), Hachey (1934), and Sandström (1915).

Briefly, the temperatures of this shallow water follow land temperatures more closely than any of the other sub-areas. Thus the annual range is greatest and the time lag of maximum or minimum temperatures from the position of the sun is least. Winter storms stir the water to homogeneous temperatures vertically. In summer a strong thermocline is developed which aids in producing high surface temperatures. South and west of Cape Cod the minimum occurs not later than the last of February. Close inshore the temperature may locally be close to 0° C., but offshore a few miles it is rarely lower than 2° C. and generally higher than 4° C. Seaward, in progressively less shallow water, a regular and rapid increase of surface warmth occurs. Near the shelf-line temperatures are from 6° C. south of Cape Cod to 9° C. off Hatteras. South of Halifax the gradient is less steep, for along the 200-meter contour the temperature is only 3° C. In general, the isotherms closely parallel the shoreline in winter.

At the opposite season the maximum temperatures from Cape Cod to Hatteras are from 21° C. to 27° C., the latter being found at Hatteras. South of Halifax the highest temperatures are between 15° C. and 17° C. At this season the isotherms show a strong tendency to parallel the latitude.

Near Hatteras the annual range is 18° to 20°, off Cape Cod about 17°, and south of Halifax 16° or less.

II. *Slope-water*

The Slope-water occupies the area which separates the "cold wall" of the Gulf Stream and the coastal water. The area fans outward from a point at Cape Hatteras to a width of

140 miles south-east of New York, narrows to approximately 110 miles off Georges Bank, and widens again to an average of about 170 miles off Nova Scotia. The width also depends on the magnitude of the migration of the Gulf Stream, for temporary wanderings of the warm surface water cause an increase or decrease of breadth. The shoreward limit is arbitrarily fixed at the 200-meter line. Seaward from the boundary line the water deepens to more than 2000 meters within a few miles. Coincident with this rapid deepening is an abrupt change of the physical, chemical, and biological characters (Helland-Hansen, 1910) of the water. Furthermore, there is a definite unity in all its properties throughout its whole expanse. Thus, factors other than surface temperature set it apart from its bordering waters.

Annual Cycle of Temperature.—Winter-time charts indicate that the minimum temperatures come in mid-March, nearly a full month later than in the shallow coastal water. At that time the water next the continental shelf is a degree or two higher than the bordering coastal water. The isotherms parallel the continental shelf-line from Nova Scotia south-westward to the bend of New York. The north-eastward trend of the isotherms from this point is suggestive of warmer water mixing with Slope-water, for the latter should be colder than it is at the high latitude. This phenomenon will be explained in fuller detail in the discussion of the Gulf Stream. From the bend at New York the isotherms continue their north-east to south-west course, trending gradually toward the coast. Even so at Cape Hatteras, where this Slope-water ends by tapering to a point, the surface temperature may be as low as 8° C. to 10° C., though in all probability this low temperature represents coastal water which has migrated just over the continental shelf (Iselin, 1936).

The slow rate of warming, after the surface has reached its minimum, until mid-May suggests that winter conditions remain well established for a period of about four months. Harwood and Brooks (1933) have computed the average monthly temperature for the width of the area on the New York-San Juan route and found it to be 13° C. for May, while it averaged 11° C. for the first four months of the year. Winter cooling and the consequent instability of the surface layers, combined with the vigorous stirring by the spring gales, form a deep layer of homo-

geneous temperature. Stability is slow to develop, but once established it is difficult to reverse, and heating proceeds rapidly. The change to summer conditions is rapid, for by mid-July the average is above 22° C. This rise is the result of the abatement of heavy spring weather by mid-May, the increase of insolation, and decreased net radiation (Smithsonian Institution, 1931). Warming continues slowly after summer conditions have become established, and the maximum temperatures arrive about the first week of September, the date of occurrence being governed in a large measure by the prevailing weather conditions. At this time the average near the western edge, adjacent to the 200-meter contour, is about 23° C. to 25° C. As is always true, the edge or transition zone, lying next the coastal water, is somewhat cooler, and the edge lying next the "cold wall" of the Gulf Stream is somewhat warmer, than the average. Between these boundary limits the difference of temperature is small in summer, 2° to 3°, but is large in winter, 5° or more.

Between Halifax and Bermuda, along the northern edge of the Slope-water area, winter minimum temperatures vary between 3° C. and 5° C. Near the "cold wall" the average minimum is considerably higher, 10° C. to 13° C., these high surface temperatures being the result of the large number of warm masses invading that portion of the Slope-water adjacent to the "cold wall," but not present at the continental shelf-line. The table shows the average winter N.-S. gradient off Halifax to be somewhat steeper than across the Slope-water between New York and Bermuda.

Throughout the year there is a very abrupt break in temperature between the coastal and Slope-water at the edge of the continental shelf south of Georges Bank, particularly on the Boston-Bermuda lane.

The average annual range is about 16° for the whole Slope-water area near its western edge, and approximately the same range near the eastern edge south of Halifax. The northern boundary has a greater range between actual extremes, approaching the range of the adjacent coastal water, while that lying close to the "cold wall" has a smaller range.

The mean annual is 16° C. to 17° C. over the western half and a degree or two lower off Halifax.

SLOPE-WATER TEMPERATURES

Location	Winter Minimum	Summer Maximum	Mean Annual	Annual Range	Temperature Gradient per 60 Miles
Close to the 200-meter contour:					
1. Off Hatteras	8°	25°–26°	17°	17°	
2. Off New York	7°–9°	23°–24°	15°–16°	16°	
3. Off Halifax	3°–5°	18°–19°	10°–11°	15°	
Close to the "cold wall":					
1. Off New York	12°–14°	24°–25°	18°–19°	11°–12°	2·5°
2. Off Halifax	10°–13°	19°–21°	16°	10°	2·6°–3·0°

Isothermal Patterns.—As a general rule, the isotherms align themselves parallel to the continental shelf, spreading out as the width of the Slope-water area increases. But during the colder months and to a lesser extent during the warmer months, this general pattern is subject to wide changes resulting from the intrusions of warm water, *i.e.* water warmer at the time of these intrusions than the Slope-water. This inflow of warm masses has a great effect on the isothermal pattern at any one time as well as on the thermal conditions of the Slope-water.

Synoptic charts made for each week, or even shorter intervals of time, show the development and life-history of the surface temperatures of these intrusions. A warm mass will appear quite suddenly and spread over a fairly large area with great rapidity. The first indication of the formation of such a mass is a slight spreading of the closely packed isotherms at the "cold wall" and a slight northern bulge in the apparent body of the Gulf Stream. The next observed condition is a more pronounced widening of the Gulf Stream to the east of the initial widening. At this stage the trend of the isotherms shows the mass to be thumblike in shape pointing toward the north-east. The isotherms converge again farther east into a bundle which marks the "cold wall." The pattern is thus indicative of an

eddy or whirl (Church, 1932 *a*, 1932 *b*; Iselin, 1936). Moreover, on the outside edge of this warm mass are irregular fluctuations in temperature, which are suggestive of smaller eddies or whirls, forming on the outer edge of the major whirl. The extent of the major eddy and its distinctness from the rest of the Slope-water is apparent from the sharp temperature gradient around the body of the mass. A southbound vessel passing through one of these masses will encounter three "cold walls"; one on the northern edge of the eddy, another on the southern edge (from higher to lower temperatures), and the "cold wall" adjacent to the Gulf Stream. In such a situation the last "cold wall" does not show as great a temperature contrast as when there is no eddy to the north.

Sources of Warm Masses.—On the charts these warm masses appear as offshoots from the warm water of the Gulf Stream, for they are always located just north of the "cold wall." They have no connection with coastal water. Only rarely do they appear to advance to the continental shelf south of Georges Bank, the narrowest part of the Slope-water sub-area. The surface warmth always greatly exceeds that of the coastal water, even in summer. Their temperatures are above that of the Slope-water, which eliminates any hypothesis that they may be formed of water of that region. The masses are most frequent and best developed during the winter and spring when there is the greatest contrast in surface temperature between the Slope-water and the Gulf Stream. The great frequency and better development (higher temperature) at this time of year, and their location along the northern edge of the Gulf Stream, seems to indicate that they must be of Gulf Stream origin. Moreover, the surface temperatures often indicate that the Gulf Stream is north of its average position as the offshoot forms. This condition appears over a small fraction of the length of the Gulf Stream. The life of each separate mass is not more than a few weeks (Church 1932 *a*). Then this northern offshoot is pinched off by a cold finger, perhaps due to upwelling, and the warmest water (Gulf Stream) is found well to the south.

These warm masses correspond to the "transgressions" of Le Danois (Hachey, 1934, 1936; Iselin, 1936). According to him a "transgression" is "a temporary encroachment of tropical

Atlantic water on water of polar origin." The amount of displacement varies considerably and appears to be a cyclic phenomenon.

Movement of Warm Masses.—These warm masses, after they have been formed, appear to have a very definite movement toward the north-east. A study of the charts made from data taken only a few days apart shows wide changes in the position of the isotherms marking the limits of the warm masses. Abnormally high temperatures occurring intermittently are not suggestive of a current, but if high temperatures are found in one place and not in another nearby at a certain time and the reverse condition is found a little later, it would appear that the warm water had moved from one position to the other. Their disappearance from one place cannot be accounted for by mixing with sub-surface water, for the area each mass occupies is too large, often 150 to 250 miles long, and the return of normal Slope-water temperatures is too rapid. The regularity of progression of high temperatures from west to east indicates movement which generally parallels that of the Gulf Stream. The velocity of the masses is not necessarily constant, though they seem to maintain a fairly constant speed after they are developed. Their velocity, estimated from the time it takes a warm mass to pass a data line, varies from 3 to 10 miles a day.

The initial momentum imparted to each mass and the driving power necessary to maintain its momentum are beyond the scope of this paper. It is quite definitely established, however, that they are not the product of the diverse gales and hurricanes of this region, though the movement of a mass may be accelerated or retarded by these heavy winds. That these masses are not torn from the Gulf Stream and driven by the wind seems evident from the fact that they are most frequent and best developed during the season when the wind is from the north-west quadrant. This wind direction would tend to throw the surface water of the Gulf Stream south into the Central Atlantic sub-area rather than into the Slope-water sub-area (Ekman, 1907, 1923). On the other hand, perhaps the Gulf Stream would have a winter position farther north-west were it not for these gales. However, the north-westerly winds and

gales of the winter and spring in all probability would force surface Slope-water southward and create a pressure tangent to the flow of the Gulf Stream. This could cause a pinching or damming of the Gulf Stream at some point and permit its warm water to move into the Slope-water sub-area. Any loss of water from the Slope-water requires compensating increments from some other bordering sub-area. The only other area, eliminating the Gulf Stream, from which water could come, is the coastal area which is relatively narrow and shallow. Floodings from this area are infrequent and only local in extent, as Bigelow (1933) has shown.

Annual Temperatures.—Owing to the temporary invasions of warm water, this sub-area is characterised by a heterogeneity of temperatures which singularly marks it off from the water of either side. Large monthly and seasonal fluctuations occur along the border adjacent to the Gulf Stream. It is difficult to determine the mean annual temperature, the mean annual range, and the monthly temperatures, because of the intrusions which may be present at one time and absent during another.

The greatest annual range occurs next the boundary of the coastal water. Here, just seaward from the zone of occasional coastal-water intrusions south-east of New York, a representative area, the minima vary between 7° C. and 9° C. (see fig. 5) and occur between the last of January and the middle of March. In the same location the maxima reach 23° C. to 24° C. sometime between the middle of August and the middle of September (see fig. 6). Approximately 16° is the mean annual range.

In winter, when no warm masses invade the sub-area, there is an even steep temperature gradient. At the time of minima temperatures the difference on opposite sides of the sub-area off New York amounts to about 5°. South of Halifax the difference is from 7° to 8°. During the shift from winter to summer conditions this difference is lessened. When summer temperatures have become fully established the amount has shrunk only 2° to 3°. At any season of the year when the Slope-water sub-area is free from warm masses, the isotherms parallel the coast east from the angle of the coast at New York, while to the south they approach and cross the coastal water at an acute angle.

III. *The "Cold Wall"*

The remarkably steep temperature gradient between the Slope-water and the Gulf Stream has long been known as the "cold wall." Though cases of differences as much as 11° within 75 meters can be found in literature, such is not a normal condition. Thermograms do not attest to such extraordinary occurrences. It is true that the records show a sharp contrast within a short distance, but never does the thermograph pen draw a line indicating a nearly instantaneous change. Examination of the records under a magnifying lens shows that it requires from half an hour to a full hour for a vessel to pass through the "cold wall." Such a time-interval indicates a width of 10 to 20 miles as an average. Therefore the temperature change equals about 1° per mile. Most of the vessels cross at right angles to the "cold wall." The average difference, when this zone is best developed (winter), is from 11° to 14°, though occasional records have displayed greater differences.

Not always does the northern edge of the Gulf Stream have this remarkably sharp boundary. Often during the winter the gradient flattens considerably and the change diminishes to 0·2 of a degree or less per mile. This occurs at the time of the movement of a warm mass into the Slope-water sub-area.

Normally during the course of vernal warming as the water to the north increases in temperature, the colder isotherms break off from the "cold wall" and move northward. The water of the "cold wall" then exhibits a progressive diminution of temperature change until there is a difference of only 2° to 4° in late summer when maximum temperatures prevail over the Slope-water and Gulf Stream. Even with this small difference for the "cold wall" the change is abrupt.

Temperatures on the extreme northern edge of the "cold wall" are often a degree or more below those on either side. Sometimes these low temperatures are not matched within 40 to 80 miles to the north (see fig. 7). This cold zone, not more than a mile or two wide, is quite consistent during the colder half-year when the temperature gradient to the north-west is even and regular. The zone is less prominent during the warmer half-year. It has been observed in all months except August. The cold temperature of this zone is obviously the result of upwelling (Church, 1932 *b*).

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IV. *The Gulf Stream*

This well-defined current has long been called any part, or even all, of the great North Atlantic circulation from the Straits of Florida to the northernmost point of the Norwegian coast. Fortunately this chaos is being cleared, in oceanographic circles at least, for the name Gulf Stream is reserved for that portion of the great North Atlantic eddy which is between the north-eastern edge of the Blake Plateau (off the North Carolina coast) and the "tail" of the Grand Banks (Iselin, 1933, 1936).

The location of the lateral edges of the Gulf Stream are not as easily defined nor located. On all steamer crossings used in this study it has been known that the Gulf Stream has made wide temporary excursions from its normal path. These lateral swingings are still unpredictable as to the time when they will start; but once started are rapid in development. A few studies have been devoted to either the course of the main temperature axis (Pillsbury, 1891), or the mean position (U.S. Coast and Geodetic Survey Chart 1007). From the thermograms which have been made it has been possible to draw true boundaries, for the first time, as shown by the temperature and temperature changes of the surface water.

McEwen has pointed out that a current can be detected from a continuous plus or minus temperature departure (McEwen, 1915). Based on this conclusion the Gulf Stream is a permanent feature of the western portion of the North Atlantic. Thermograms at all seasons of the year show it as a distinct and separate narrow ribbon of hot water clearly different in temperature, and thus of origin, from that on either side. (See fig. 7.) Its temperature is always higher than that which lies next to it, even during the summer months.

Width of Gulf Stream.—The Gulf Stream is narrowest where the water of the Florida Current flows off the shallow Blake Plateau to form the Stream. At this point, south-east of Cape Hatteras, surface temperatures show a width of approximately 50 miles. Occasional narrow bands of warm water, seaward from the main body of the Gulf Stream, are probably the last remnants of the so-called Antilles Current and the Northern Equatorial Current which have not as yet become incorporated

in the Gulf Stream or body of the wide Central Atlantic (Sargasso Sea) sub-area. These bands do not properly belong to the Gulf Stream for they are not a permanent characteristic. However, they do account for former statements that the Gulf Stream was 150 miles* wide off Hatteras (Marmer, 1929; Pillsbury, 1891). In the Straits of Florida the average width of the Florida Current, as figured from surface temperatures, is about 42 miles, and this point is more than 700 miles to the south of Cape Hatteras. Thus the surface widening of this rapidly moving current is slow indeed. Off Cape Hatteras some Gulf Stream water spreads over the continental shelf, for Diamond Shoals Light Vessel, anchored in 55 meters of water, reports an average dominant set of the water of 0·4 knot to the north-east (Marmer, 1929).

Eastward 165 miles from the Cape, where vessels on the New York-Puerto Rico route cross the Gulf Stream, the width is about 55 miles, the mean determined from eighty-three charted crossings. These widths were computed by measuring the distance between the lowest temperature on the southern edge and the corresponding temperature on the northern edge. Variations of great magnitude have occurred during the period of observation. Twice it has been less than 30 miles wide and six times has been between 30 and 40 miles. Five times it has been more than 80 miles wide, two of which were in excess of 100 miles.

Vessels on the New York-Bermuda route cross the Gulf Stream approximately 300 miles north-east of Hatteras. At this crossing-point, using data from sixty-five charts, the mean width is about 58 miles. Here its width has never been less than 30 miles, but nine times it was less than 40 miles. In contrast, it was more than 100 miles wide no less than six times. East of the Bermuda lane some 400 miles is the Halifax-Bermuda route. Only eighteen crossings have been charted, but these give an average width of 62 miles. Even with these scant data great variations in width, similar in magnitude to those mentioned above, have occurred.

* Iselin (1936, p. 12) gives 130 miles as the average just north of the Cape. Here he uses a velocity (10 cm. per second) as a criterion. Using this same definition for the Gulf Stream he finds it only slightly wider off Nova Scotia.

Though the Gulf Stream shows variations in width from less than 30 miles to more than 130 miles at each of the steamer lanes, except off Hatteras, there is no simultaneous broadening or narrowing over its whole length. At any one time the Stream may be broad on the New York-Bermuda line, narrow on the New York-Puerto Rico line, and broad again between Halifax and Bermuda. Any other possible combination of narrow and wide places may exist. This widening is the result of warm masses debouching from the Gulf Stream into the cooler water of the Slope sub-area. The charts show that warm masses have broken off at any point along the length of the Gulf Stream from Cape Hatteras to the longitude of Halifax. It is probable that these warm masses have also broken off from the Gulf Stream between Halifax and the "tail" of the Grand Banks.

An analysis of the data on the New York-Puerto Rico route indicates but slight, almost negligible, difference in the average widths for the colder half-year (January to July) as against the warmer half-year (July to January). The latter averaged 54 and the former 56 miles. No other crossings have been analysed, for the data period has been of insufficient length.

Annual Cycle of Temperature.—From west to east over the observed part of the Gulf Stream there is but little temperature difference at any one time. However, such differences as are found are significant, for they represent the relative amount of cooling which it experiences on its eastward journey.

To proceed from the least complex to the most complex condition is the normal method of diagnosis. In discussing the temperature régime it appears less confusing to start with minimum temperatures and proceed through the period of warming to the maxima and then through the period of cooling back to the minima to complete the yearly cycle.

South-east of Cape Hatteras, where the Panama-Pacific vessels cross the Gulf Stream at an acute angle, the lowest readings come during February and early March, with a secondary minimum in April. The lowest average is about 23° C. These do not persist long, for the increasing insolation of the northbound sun, the lessening velocity of the winter-time continental winds, and the higher temperature of the water issuing from the Straits

of Florida all combine to cause rapid vernal warming (Brooks and Fitton, 1930). Minimum figures occur nearly simultaneously along the whole length of the current, but are somewhat lower to the east. Representative temperatures are 22° C. on the New York-Puerto Rico line, 21·8° C. on the New York-Bermuda line, and 20·5° C. on the Halifax-Bermuda line. Thus over this portion of the Gulf Stream's length the temperature is lowered some 2·5° within a distance of about 800 miles. This is comparable to a cooling of 1·5° between the Straits of Florida and Cape Hatteras, approximately 800 miles also, at this time of year.

Spring-time warming is rapid, for by the beginning of June the temperature off Hatteras is nearly 27° C., while farther east 26° C., 25·5° C., and 25° C. are average. Though the increase in temperatures is by no means complete at this time, summer-time conditions may be considered as well established. Warming still continues during the following three months, but owing to the greater net radiation the rate is slower.

Maximum temperatures are manifest by the end of August or early September. At this time we find temperatures from about 29° C. to 29·5° C. at Cape Hatteras to 28° C. south of Halifax. Thus the surface of the Gulf Stream cools about 1° during its journey in the summer as compared with 2·5° in winter. Again this temperature difference compares favourably with the difference observed between the Straits of Florida and Cape Hatteras, for while the latter has a temperature of 29° C. to 29·5° C., the former is 30° C. to 30·5° C., or 1° higher. Summer conditions remain fairly constant until October when autumnal cooling increases in rate. By the middle of October the temperatures are almost exactly those of the first week of June. Decreased insolation, greater net radiation, increased contrast between air and water temperatures, and frequent heavy winds and storms all operate to bring the surface to winter temperatures by the beginning of the year (Brooks, 1932). From that time until the minima are reached cooling is slow.

Annual Range of Temperature.—From the discussion of the annual cycle of temperatures it is apparent that the annual range is small for the high latitude of the Gulf Stream. Owing to this small range, 6° off Cape Hatteras and increasing up to only

8° south of Halifax, it follows that this water must be of tropical origin. Water of the Slope-water sub-area, it will be remembered, has about a 15° range, and, as will be seen later, the adjacent part of the Central Atlantic sub-area has a range greater than that of the Gulf Stream. This eliminates the possibility that surface water of the Stream can come from the surface of either of these other sub-areas.

Gulf Stream Temperatures

Location	Winter Minimum	Summer Maximum	Mean Annual	Mean Annual Range	Width (Nautical Miles)
1. Off Hatteras	23°	29·5°	26°	6·5°	50
2. S.E. of New York	22°	29°	25°	7°	55
3. South of Halifax	20·5°	28°	24°	7·5°	62

Departures from the Average.—From the annual régime, averages for any period can be computed. Then by comparing these averages with those that are found at any analogous period the amount of departure, if any, is shown. Though there have been a number of minor departures, less than a degree, only one large departure has occurred during this period of study. During the fall of 1930 and the following winter, cooling was greater than customary, for the winter minimum off Cape Hatteras was a full degree lower than the average. This minus temperature departure persisted until the summer of 1931 when the opposite condition developed with the surface, attaining a +1° departure as far east as the longitude of Halifax.

Though this is the only marked case of departure, it is indicative of the fact that outstanding anomalies can and do occur even where the annual range is quite small. Surges of water with plus or minus departures have been accounted for by varying trade wind strength (Brooks, 1931) in addition to the effect of atmospheric extremes from North America.

Simultaneously with Gulf Stream departures came departures of the same sign, though not as great in magnitude,

over the western part of the wide Central Atlantic sub-area. It is likely that as the Gulf Stream carries this water of anomalous temperature along its course there will be similar departures along the northern edge of the Central Atlantic with an increasing time lag toward the east. In any event, any persistent cooling weather would influence both at once.

Bands of Warm Water South of the Gulf Stream.—Frequently in the colder half-year, particularly during the two months of lowest temperatures, there may be one, two, or even three narrow bands of warm water which lie close to the southern edge of the Gulf Stream. That these warm bands are not isolated warm masses, comparable to those found in the Slope-water sub-area, is evidenced by their presence over all routes. A series of charts, representing several weeks, shows that they develop slowly and disappear slowly, quite in contrast to the Slope-water warm masses. The temperature of each succeeding band away from the Gulf Stream is progressively lower; the final one having a temperature not more than half a degree higher than that of the Central Atlantic sub-area itself. In general, their temperatures, which set them apart from the Gulf Stream and the Central Atlantic sub-area, decrease toward the east, so that in the longitude of Halifax the bands are poorly defined and infrequent.

The bands are absent during the warmer half-year, or at least not prominent enough to be detected. At this time of year there is but little difference in temperature, 1° to 2°, between the Gulf Stream and the Central Atlantic sub-area.

These bands may be the last remnants, restricted in width, of the wider distinct thermal bands found in the Northern Equatorial Current.

Temporary Migrations of the Gulf Stream.—In its flow from west to east the Gulf Stream is seldom, if ever, in its average position or course. Lateral wanderings occur, which are small and minor, at Cape Hatteras, but increase in magnitude of swing toward the east. At Hatteras the main body of the Gulf Stream flows along the seaward side of the continental shelf. Some of the water apparently floods a portion of the continental shelf, for meanderings of the Gulf Stream alternately place the Diamond Shoal Light Vessel in coastal water and Gulf Stream water.

Owing to the angle at which vessels carrying thermographs cross the Gulf Stream at this point, it is quite impossible to determine accurately the amount of swinging back and forth. It is probable, however, that the meanderings do not greatly exceed 30 or 40 miles.

Beyond the point where the Gulf Stream impinges on the continental shelf, its migrations become more pronounced. This is partly the result of the spreading of the warm water and the detaching of warm masses. Though the latter have at one time or another occupied virtually all of the Slope-water sub-area, much of the area north of the average position of the Gulf Stream cannot rightfully be said to have experienced the presence of the Gulf Stream proper. Due south-east of New York, 300 miles north-east of Cape Hatteras, the average position for the northern edge is approximately 240 miles distant, but it has been within 180 miles. At this steamer crossing the southern edge has been nearly as far north as the mean position of the "cold wall." Migrations of the same magnitude have occurred south of the mean position making the total distance of lateral swinging for the Gulf Stream approximately 120 miles at this data line. Progressively toward the east the migrations assume a greater magnitude. During the short period of record available for the Halifax-Bermuda route the northern edge of the Gulf Stream has been within 230 miles of the coast and as far away as 420 miles, though its average position is about 290 miles. Close approaches of the Gulf Stream in this longitude result mainly from the almost semipermanent character (as long as six weeks) of the warm masses, Gulf Stream water flowing into each for such a period that the surface temperature of the warm mass comes to nearly the same temperatures as the parent mass. When a warm mass becomes detached the main flow of the Gulf Stream continues well to the south.

Not always are the lateral swingings caused by the formation and detaching of warm masses. Frequently in summer, when warm masses are absent or poorly defined, the course swings from its normal position. Even so, the magnitude of these digressions, both winter and summer, is such that there is no indication of a definite seasonal or cyclic shifting, for it is as apt to be as close to the continent in winter as in summer.

V. *Central Atlantic*

South and south-east of the Gulf Stream lies the wide expanse of warm water whose surface temperatures are characterised by greater homogeneity than those of the sub-areas previously discussed. The southern edge is poorly defined if its limit is to be set by surface temperatures alone. In the final analysis, factors other than, and in addition to, temperatures will have to be employed to set its equatorward boundary. For the western part of this sub-area, where it is crossed by the New York-Puerto Rico route, Harwood and Brooks (1933) used the point where there was no further increase of temperature with decrease of latitude as the southern extremity. They found the sub-area to be wider in winter than summer, attributing this to the compensating broadening of the Antilles water by the northerly position of the summer sun. According to them the average width is 828 miles; its summer width (June to September) is 787 miles and its winter width (December to March) is 860 miles. Not only does this sub-area vary in width depending on the seasonal change of the breadth of the Antilles water, but also the variations of the position of the Gulf Stream obviously cause temporary and rapid changes of width.

Farther east, on the New York-Cape São Roque route which crosses this sub-area at an angle, greater fluctuations of width from winter to summer develop. In a previous paper (Church, 1934) I suggested the possibility of using the line of 6° annual range as the mean position for the southern limit. The summer boundary is about 300 miles to the north of this location (approximately 24° N. Lat., 53° W. Long.), the point at which there is no increase in surface temperature with lower latitude. At this time the width of the sub-area is very nearly the same as that farther west; namely, 800 miles. This northward movement of the limit cannot be explained on the basis of an increase in volume of the Northern Equatorial Current, for the change in width is far too great. One possible explanation is the greater heating power of the summer sun which brings the temperature of the surface water of the southern part of the Central Atlantic sub-area up to the warmth of the northern part of the Northern Equatorial Current.

Greater net radiation and lesser insolation in the winter-

time permits the southern edge to migrate far to the south, thus widening it some 600 miles from the summer conditions or to 21° N. Lat. at 52° W. Long. Half-way between this point and the same latitude on the New York-Puerto Rico line, thermograms from the Canadian National Line, between Bermuda and the Lesser Antilles, show a somewhat smaller change from summer to winter widths.

Temperatures.—The annual régime of temperature for this sub-area follows that of the Gulf Stream very closely. Minima occur from late February to late March along that portion which borders the Gulf Stream, and varies between 19° C. and 20° C. south-east of New York. South and south-west of Bermuda there is a gradual increase of temperature to approximately latitude 21° N., the southern limit of this sub-area at this season. Here the temperature is between 25° C. and 26° C., a rise of 5° to 6° from that of the northern edge, 800 to 1000 miles to the north. No appreciable difference of temperature exists along the southern edge between the longitudes of the New York-Puerto Rico and the New York-Cape São Roque routes.

The whole sub-area warms simultaneously in spring and summer owing to the small net radiation and the increasing intensity of the northbound sun. Also, heavy weather is for the most part absent. Conversely in fall and early winter the cooling of the superficial layers occurs without time lag of any portion.

From the minimum of late winter, surface warmth increases slowly and uniformly, interrupted along the northern edge only by the bands of warm water which are occasionally present, until the maximum is reached between the middle of August and the middle of September. Next to the Gulf Stream the temperature increases fully 8° from its winter condition to 27° C. or 28° C. north of Bermuda. Summer maxima are fractionally higher to the west of Bermuda and slightly lower to the east.

South from the Gulf Stream the temperatures increase slightly, and in summer attain their maxima north of Puerto Rico near the 26th parallel. North-east of Puerto Rico, on the Cape São Roque route, the highest temperatures are found in approximately the same latitude. Along this parallel the temperature reaches 29° C. to 30° C. The position of this line

of highest temperatures closely corresponds to the axis of the Azores-Bermuda HIGH, where at this season there is a minimum of wind, and therefore a minimum of surface stirring, the development of a strong thermocline, and a maximum of intense sunshine. This line of maximum temperatures also corresponds to Meyer's line of subtropical convergence (National Research Council, U.S.A., 1930).

South from the high temperature axis the water is only a fraction of a degree to a whole degree cooler, 28·5° C. to 29·5° C., and remains so with unchanged temperature as far south as the latitude of Puerto Rico.

The annual range of the western and northern part of this sub-area is considerably more than that of the Gulf Stream, but the annual range of the southern part of the Central Atlantic is similar to that of the northern end of the Florida Current and the south-western part of the Gulf Stream. Whereas the Gulf Stream has a range of about 6° off Cape Hatteras, the adjacent part of the Central Atlantic has a range of at least 9° to 10° and even more in the extreme western portion. This latter portion, which has the greatest range, is subjected to the cold polar air which flows south-eastward with a high velocity and great frequency from the interior of the continent in the winter and exerts its greatest influence on the water north of Cape Hatteras. South of the summer-time southern edge of this sub-area the annual range diminishes rapidly from approximately 8° to 6° in latitude 23° N. off Puerto Rico, and is the same in latitude 25° N. south-east of Bermuda. At the position of the winter-time southern edge, the annual range has decreased to approximately 5·5°.

Temperature Departures.—As previously mentioned, departures from the normal occur in the western part of this sub-area and are of the same sign and time as those which develop in the Gulf Stream. However, the magnitude of the departures is not as large as those of the warmer water to the west and north, being from one-half to three-fourths as much. Nevertheless there is a strong possibility that these smaller departures, as compared to those of the Gulf Stream, exert a greater influence in producing weather abnormalities along the eastern seaboard of the United States than does the warmer but narrow Gulf Stream. Such a statement is based on the fact that the southern

half of the Central Atlantic sub-area, together with the northern part of the Northern Equatorial Current, constitutes the source area for the tropical Atlantic air masses which move or spread westward to the eastern seaboard and then northward to the latitude of Boston before great changes in the lower layers develop. (Willett, 1933). The time during which the air is in contact with the water of the Central Atlantic sub-area is far greater, thus allowing a greater accumulation of heat, than in passing over the narrow Gulf Stream.

VI. *Northern Equatorial Current*

From the southern boundary of the Central Atlantic sub-area to the north coast of South America and east of the Lesser Antilles is the Northern Equatorial Current. It is the sub-area having the least automatically recorded data with which to work. However, its low latitude results in small temperature changes from month to month and year to year. Thus one complete year of record is of great value and far safer on which to base some conclusions, except departures from the normal, than would be true for any of the other sub-areas. Data are available along two routes in this sub-area: the Cape São Roque line of crossing from New York, and the line between Cape São Roque and Trinidad. Two other lines are of value for this sub-area though both lie just outside the limit: viz. the route from Trinidad northward through the Anegada Passage, and the other from Georgetown, British Guiana, northward following the line of the Lesser Antilles.

At its widest reach (north of Cape São Roque) this sub-area is more than 1500 miles wide. In spite of this great north-south distance, however, there is a striking similarity of surface temperature. An analysis of the thermograms shows at least three belts which are more or less clearly different, resulting from slightly different surface temperatures. In a paper (Church, 1934) I tentatively called them the "northern belt," "central belt," and "equatorial belt." Each of these belts has a somewhat different salinity content and probably other differing physical properties. This is suggestive of somewhat different sources for each of these belts, or a difference of factors which influence the physical properties of each belt.

The Northern Belt.—The northern belt, on the Cape São

Roque route, covers the distance between the southern edge of the Central Atlantic sub-area and approximately 15° N. Lat. The southern edge is not fixed at the latter latitude, but varies from year to year as well as from season to season. It is poorly defined or absent during a large part of the year, but during the winter and spring a sharp change of temperature, from one-half to a whole degree, within 20 to 30 miles, is perhaps sufficient justification for use as a surface temperature boundary. This break in temperature is consistently present each year. The latitude (15° N.) closely coincides with the southern edge of a high salinity (37 parts per M) belt (Iselin, 1936).

Temperatures.—As with the other sub-areas to the north this one has the minimum occurring at least two months behind the position of the sun, for the surface is coolest from late February to late March. Over the northern half (south to approximately 17° N. Lat. at this season) the surface is between 23·4° C. and 24·5° C., and the southern part is between 24·5° C. and 25° C. Warming progresses slowly during the spring and summer, for the maxima are not fully established till September and occasionally as late as early October. During the period of highest temperatures (August through October) the whole belt has about the same surface temperature, *i.e.* 28·5° C. to 29° C., the cooler water generally lying in the southern half. Cooling takes place rather rapidly in late fall and winter to bring the temperatures back to the winter minima to complete the yearly temperature cycle.

Across the western part of this sub-area, viz. along the route north from Trinidad through the Anegada Passage and thence direct to New York, the data show that this belt has narrowed considerably from its great width to the east. Though the summer-time northern edge lies in approximately the same latitude as that on the New York-Cape São Roque route (27° N. Lat.), the winter-time boundary is clearly marked at latitude 22° to 23° N. The southern edge of this belt, distinct in winter and spring only, lies in latitude 17° to 18° N., the latitude of Antigua. The change of temperature which marks this edge does not correspond to the northern end of the chain of the Lesser Antilles. Thus the islands do not effect a temperature change even though the data were taken on the route that lies on the lee-side of the islands. The temperature remains constant

from the north coast of Trinidad to the above-mentioned latitude with no evidence of alteration of warmer and cooler water which might be expected where a line of islands lies athwart a current.

North from the islands in the winter the temperature slowly decreases with increasing latitude. In the summer in this belt the reverse is true, for the water north of latitude 18° N. is fractionally higher than that to the south.

The northern part of the northern belt has a smaller annual range than the contiguous Central Atlantic sub-area. This is the result of the sharp temperature increase, which forms the boundary between these two sub-areas, during the season of minima temperatures. As a result the northern half has an annual range of about 5°. The southern half, owing to higher winter minima, has a range of only 4°. Close to the Antilles, in the western part of this sub-area, the annual range shrinks fractionally to only 3·5°.

The Central Belt.—North-west of Cape São Roque the central belt is set apart from the northern belt by a rapid change of surface warmth in the coldest months similar to the boundary between the Central Atlantic and the northern belt. The belt extends southward from approximately latitude 15° N. to 5° to 7° N., where the annual régime begins to shift from that which normally occurs in the northern hemisphere to a régime showing some, but not all, of the characteristics of the southern hemisphere régime (see fig. 8). The central belt also corresponds to one of homogeneous salinity (36·25 parts per M) (Iselin, 1936), which is less saline than that of the northern belt, but more saline than that of the equatorial belt.

Temperatures.—At no time or place does this belt have a minimum below 25° C. This gives a yearly range of 4° at most, though generally the range is fractionally less, as the maximum in early fall only slightly exceeds 29° C. Obviously this belt should have a lower range than any to the north owing to its lower latitude. Aiding in the production of this small range is the condition of higher minima than the contiguous northern belt. The maxima are slightly lower than the maxima of either the northern belt or the Central Atlantic sub-areas.

South of latitude 16° N., in the longitude of Trinidad, the central belt has contracted to a width of only 360 to 420 miles, due largely to the configuration of the north coast of South

America. Here the central belt occupies all the remaining distance between the latitude of Antigua and the coast of South America. Over this portion of the sub-area the temperatures are very nearly uniform across its entire width at all seasons. The lowest are at the time of year that is normal for the northern hemisphere, February and early March, and average about 26° C., a full degree higher than those north-west of Cape São Roque. The maxima come in early fall, September and early October, and average slightly more than 29° C., the same as those some 700 to 1000 miles to the east. The annual range is less than 4°.

Near Cape São Roque, along the southern edge of this belt, the minimum is produced in February or March. Surface warmth increases slowly but normally until June, at which time a small but noticeable decrease sets in. July averages colder. June, August, September, October, and November are warmer than July. This secondary July minimum is the first indication of the southern hemisphere temperature régime, which makes its initial appearance some 300 to 400 miles north of the equator, north-west of Cape São Roque (see fig. 8).

The Equatorial Belt.—The equatorial belt is considered as all the area south of the central belt. It is widest, therefore, north of Cape São Roque, and tapers to a point near Trinidad. The speed of this portion of the Northern Equatorial Current is rapid, particularly north of the mouth of the Amazon river and off the coast of the Guianas where north-west trends of the coast in reality form constrictions. From supplementary data furnished on the thermograms of the São Paulo Tramway, Light, and Power Co., Ltd., the average speed of the vessels is 395 sea miles in twenty-four hours or an hourly speed of 16·04 knots. Between Cape São Roque and Trinidad the average day's run is 443 sea miles, or an hourly speed of 18·45 knots. Thus along this coast there is an average speed of approximately 2·4 knots. Not infrequently do these vessels, when sailing along the Guiana coast, report a negative propeller slip, or the vessel travelled farther than the propeller, at the unattainable 100 per cent. efficiency, would drive the vessel.

Temperatures.—From the northern boundary south to 2° to 4° N. Lat. the minimum, 27° C. to 27·5° C., is attained in February or March. This is followed by slow warming until

June, at which time a pronounced secondary maximum, 28° C. to 28·5° C., is produced. The following three months are cooler, 27·5° C. to 28° C., than the June maximum, but warmer than the February minimum. The primary maximum is reached in late fall, October and November, the surface warmth then being from 29° C. to 29·5° C. After the maximum has developed the temperatures drop rapidly until the winter minimum is established. The annual range is from 2° to 2·5°.

Between 2° N. Lat. and the equator the annual range is the least of any place in the North Atlantic covered by this paper. The June and November maxima are nearly 28·5° C., and the lowest minimum, which comes in August, is slightly below 27° C. The annual range is thus only 1·5° to 2°.

South of the equator to Cape São Roque the southern hemisphere temperature régime is much clearer than just north of the equator. The February to March minimum has disappeared entirely, but has not yet developed into the maximum, since the greatest warmth occurs from early April to June, the temperature being 28·5° C. (see fig. 8). Cooling brings the surface to lowest temperatures during August and September (26° C. to 26·5° C.). By November the rise in temperature has started and continues until it attains its maximum value in April.

Summary

From thermographs carried by commercial vessels over various routes of the western North Atlantic, enough data have been assembled to make an accurate study of the temperature pattern, the yearly cycle, and the annual range, and also to give an indication of the magnitude of departures. This portion of the Atlantic has a number of sub-areas, each of which is more or less clearly defined from bordering waters by definite surface thermal characters.

The coastal water, covering the continental shelf, has the greatest annual range, amounting to 16° to 20° or more. The minimum comes at the end of February, when close to land the temperature is within a few degrees of 0° C., and an even steep temperature gradient exists out to the 200-meter contour. Summer temperatures vary from 16° C. to 27° C., the latter being found near Cape Hatteras and the former along the Scotian coast.

The Slope-water occupies the area between the coastal

water and the "cold wall." Owing to temporary travelling intrusions of tropical water this sub-area seldom exhibits a regular isothermal pattern. The temperature is coldest next the coastal water and warmest next the "cold wall" at all seasons. The Slope-water has a higher mean annual temperature than the coastal water. The annual range amounts to 10° to 16°, the greater range being nearest the continent.

Of all the sub-areas the "cold wall" has the steepest temperature gradient, averaging from 0·5° to 1·0° per mile. It is seldom less than 10 miles wide and rarely more than 40 miles wide.

The Gulf Stream, seaward from the "cold wall," is a band of hot water which in width averages less than 50 miles off Hatteras and less than 70 miles off Halifax. At times, predominantly in winter, the Stream may widen to double its average width owing to the debouching of warm masses into the Slope-water area. This condition is less frequent in summer. The Stream has an annual range of 7° to 9° between Hatteras and Halifax, and a mean annual averaging about 24° C.

The Central American sub-area extends from the Florida Current and Gulf Stream on the west and north to the Northern Equatorial Current on the south. The annual range is greater than that of the Gulf Stream where the two are contiguous. An even, flat temperature gradient exists over the width of the sub-area in winter, but in summer this condition is present as far south as 27° N. Lat. where the temperature occasionally reaches 30° C. Near the southern edge the annual range is less than 6°. The mean annual temperature is about 25° C.

The Northern Equatorial Current, which occupies the remaining area south to the north coast of South America, has three distinct thermal belts. The northern, whose southern edge is near the 15th parallel, has annual range of approximately 5° or less, and a mean annual of about 27° C. The central belt, less saline than its northern neighbour, has a mean temperature of 27·5° C., and an annual range of 2° to 3°. The equatorial belt, which occupies the remaining distance south from about 5° to 7° N. Lat., displays the first evidence of the southern hemisphere temperature cycle. The annual range is 2° or less, and the mean annual is from 27° C. to 28° C. Near Cape São Roque the maximum arrives during April to June, and the minimum from August to September.

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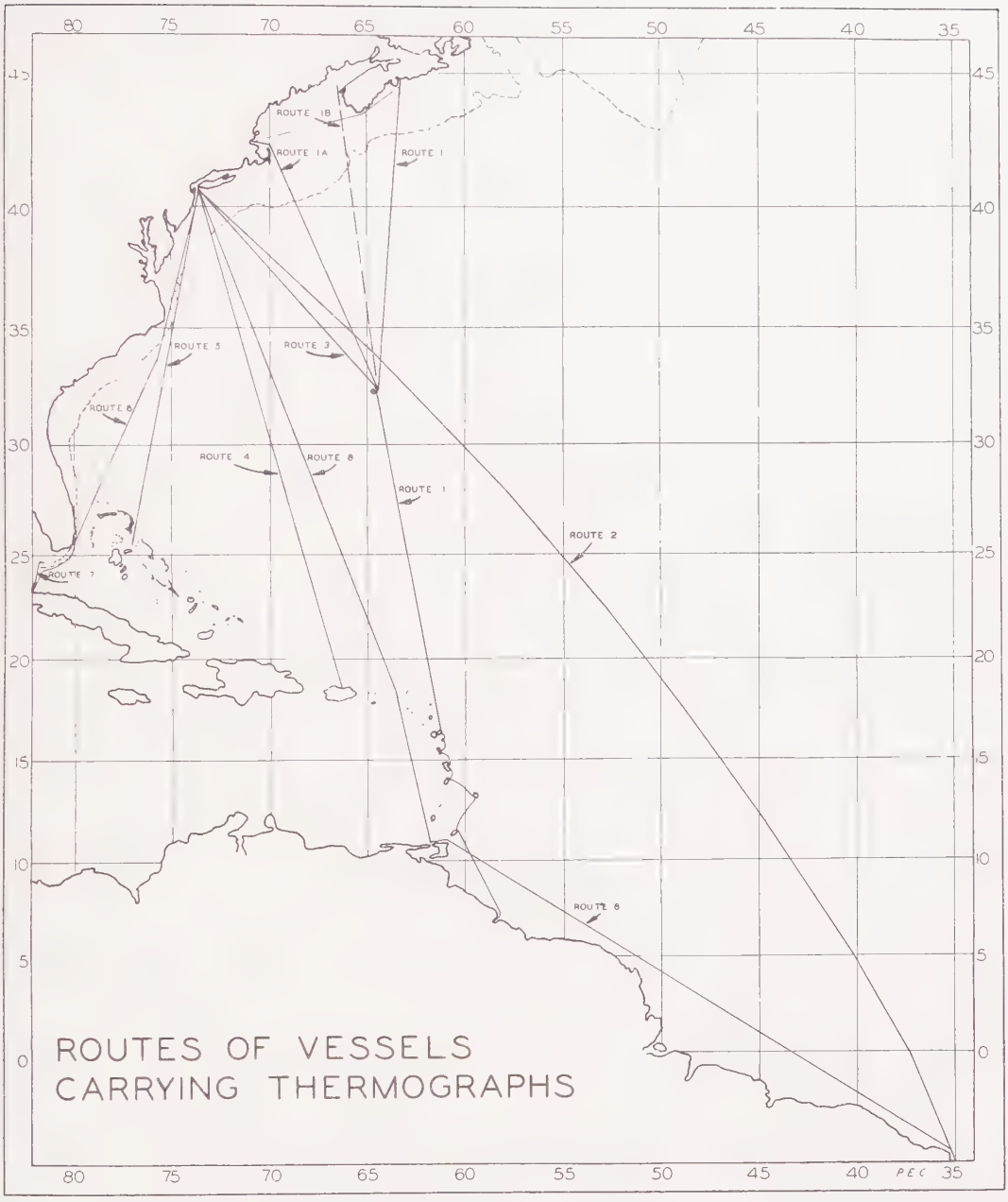
ROUTES OF VESSELS
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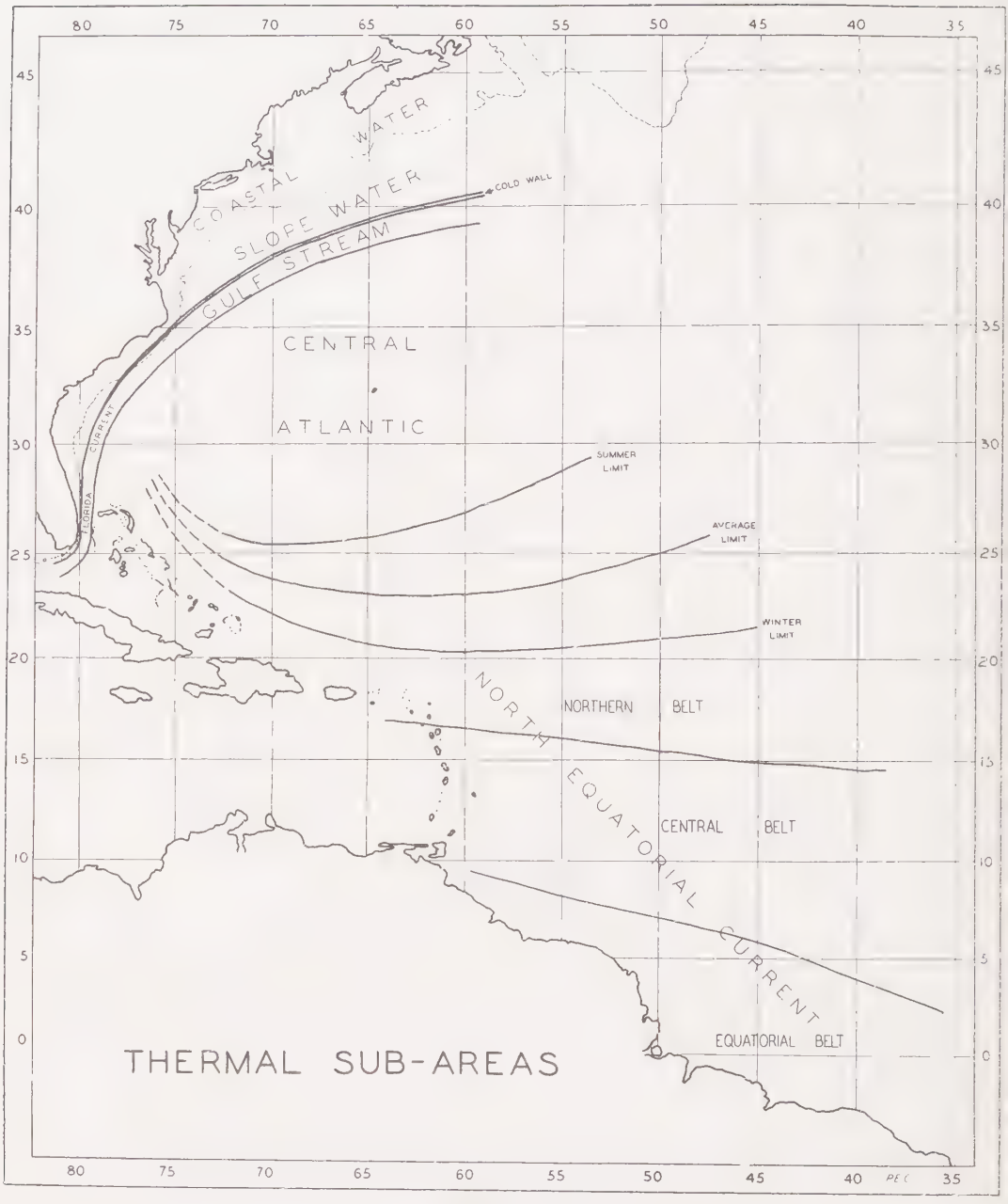
Fig. 1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SLOPE WATER
COLD WALL
GULF STREAM
CENTRAL
ATLANTIC
FLORIDA CURRENT
SUMMER LIMIT
AVERAGE LIMIT
WINTER LIMIT
NORTH EQUATORIAL CURRENT
NORTHERN BELT
CENTRAL BELT
EQUATORIAL BELT
THERMAL SUB-AREAS

Fig. 2

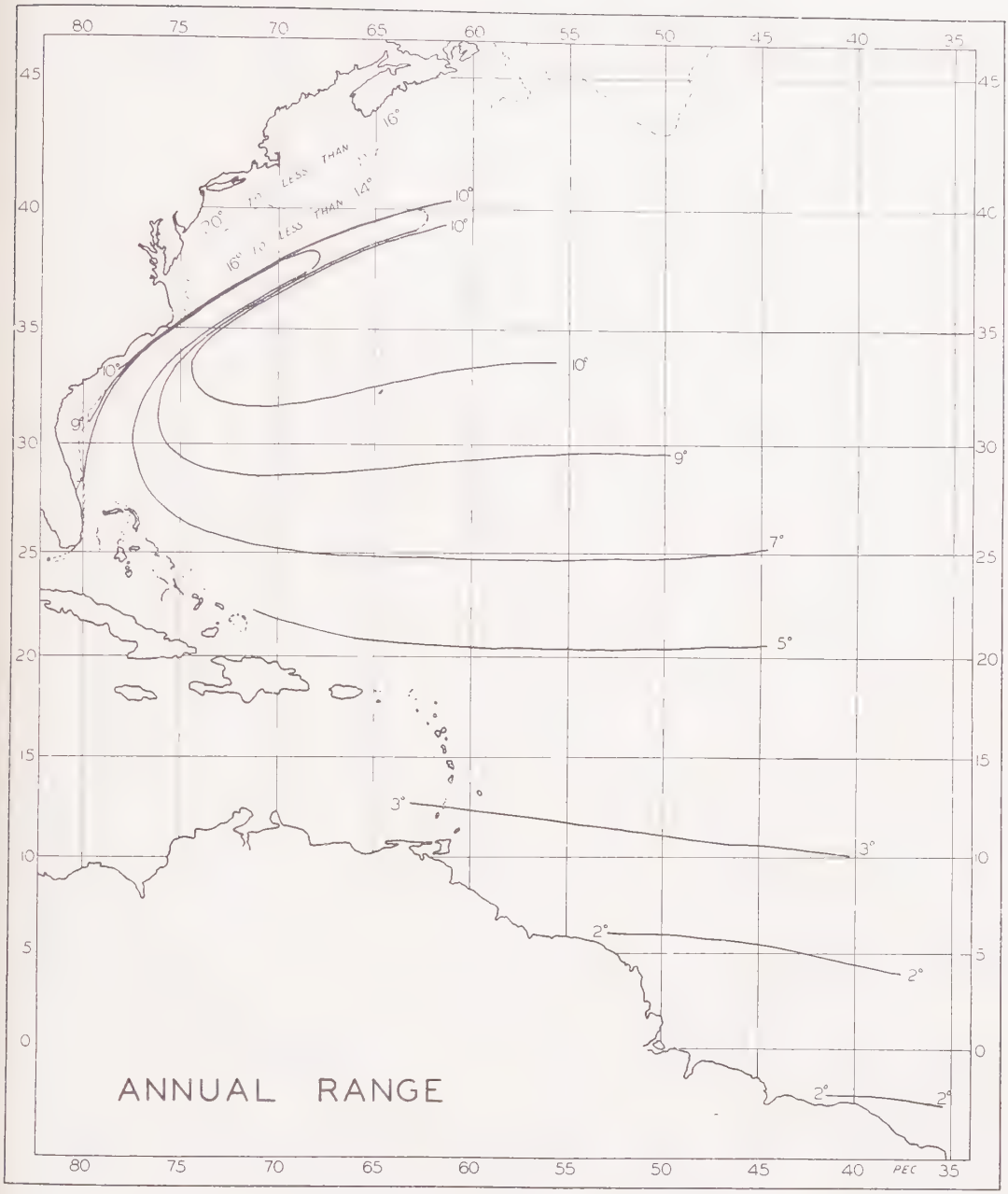


Fig. 3

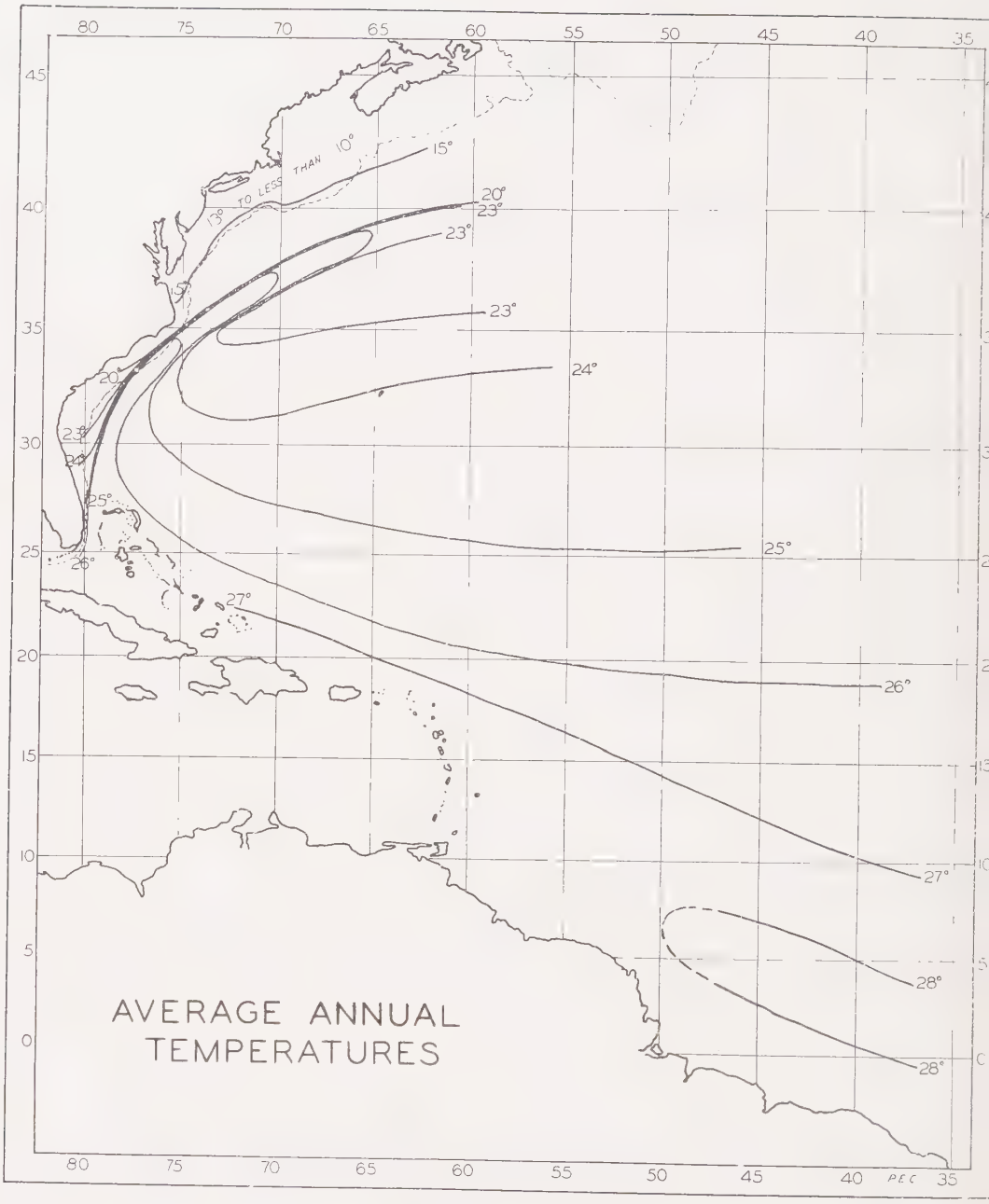

80 75 70 65 60 55 50 45 40 35
45 40 35 30 25 20 15 10 5 0
13° TO LESS THAN 10°
15°
20°
23°
23°
23°
24°
25°
25°
26°
27°
26°
27°
28°
28°
AVERAGE ANNUAL
TEMPERATURES

Fig. 4

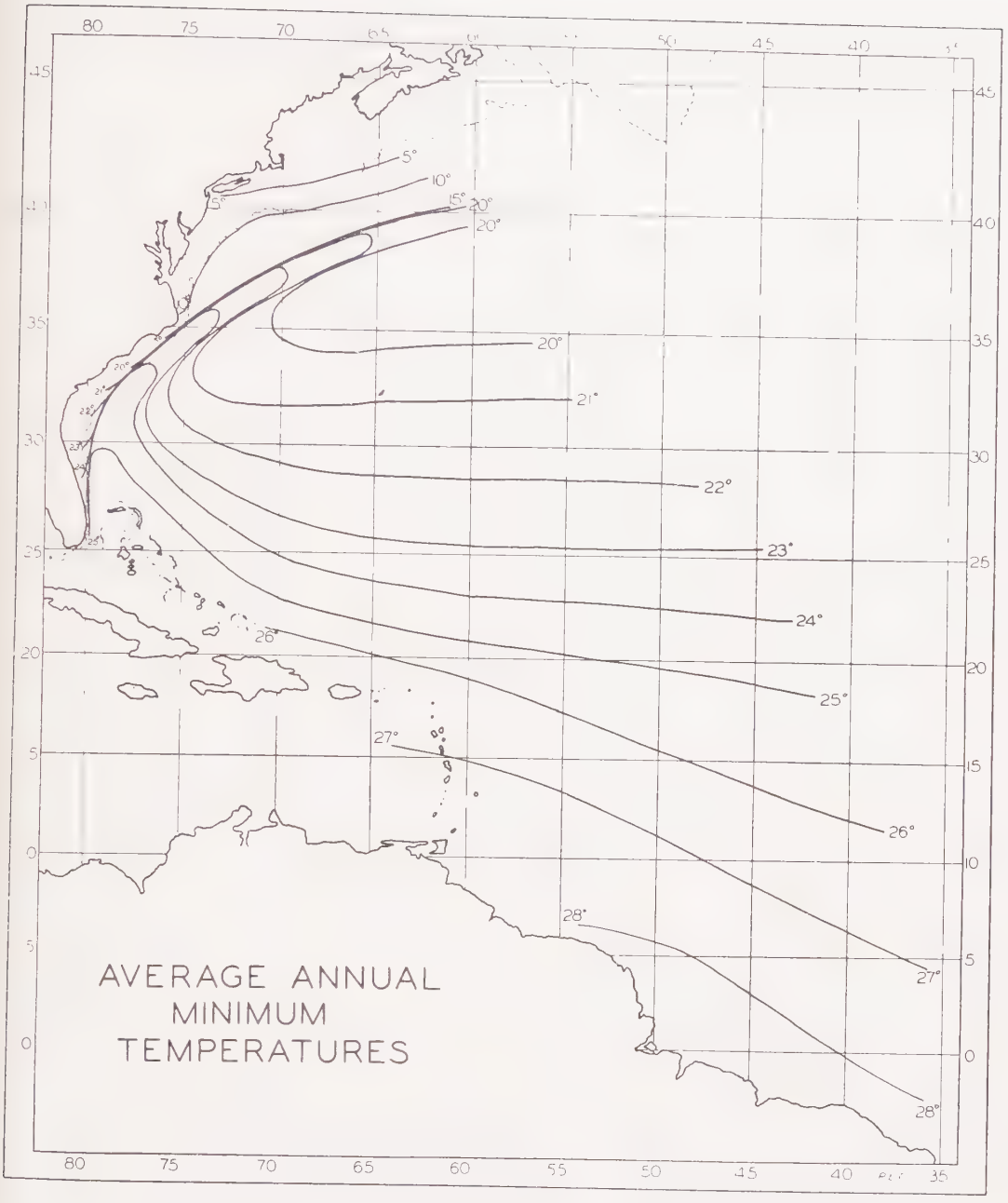

AVERAGE ANNUAL
MINIMUM
TEMPERATURES
5°
10°
15°
20°
20°
20°
21°
22°
23°
24°
25°
26°
27°
28°
28°

Fig. 5

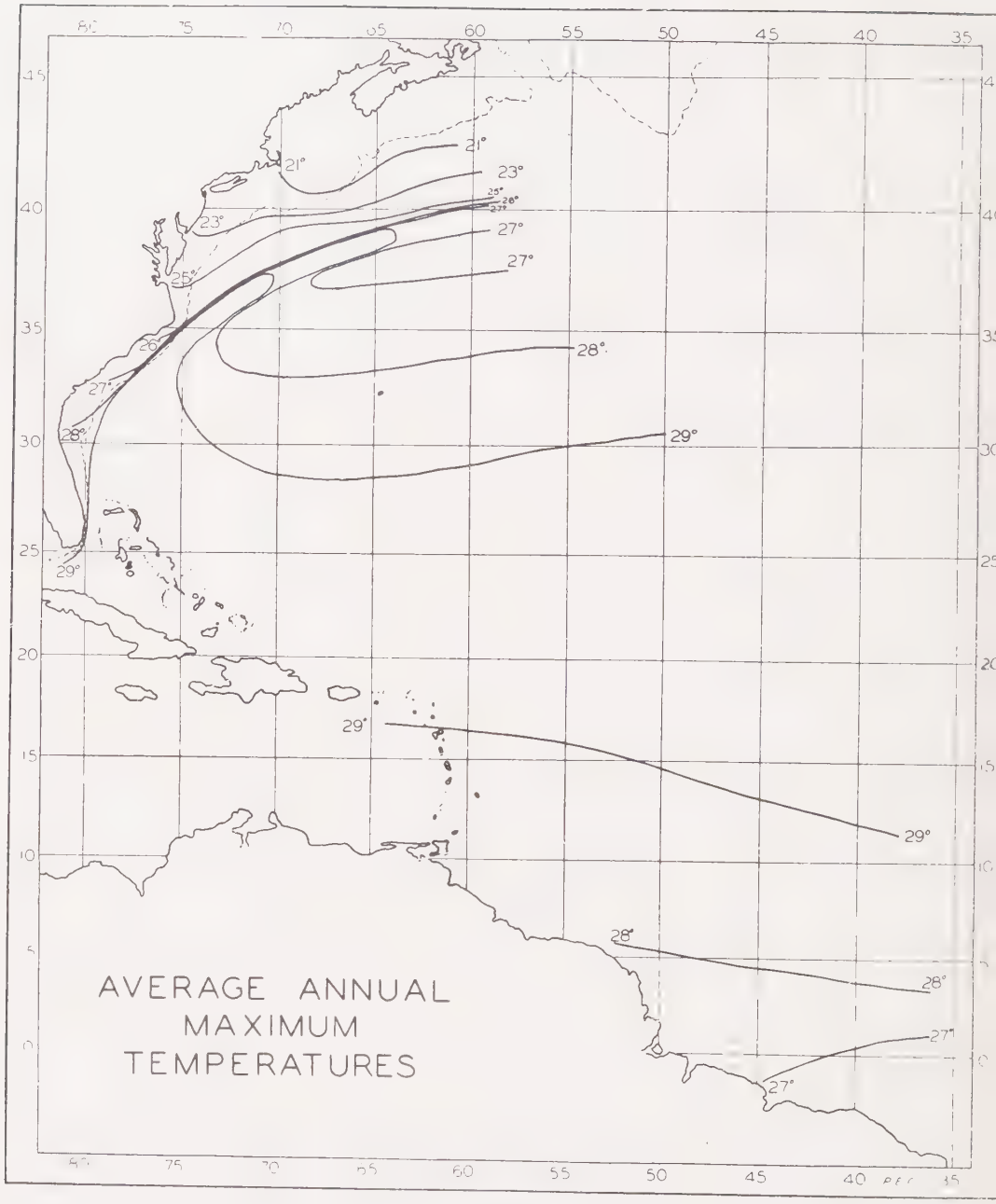
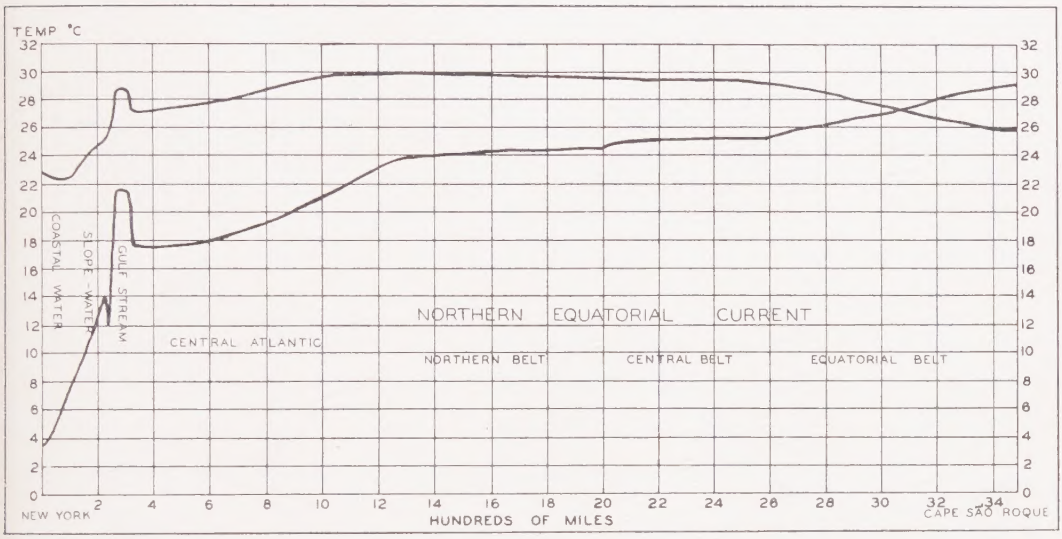
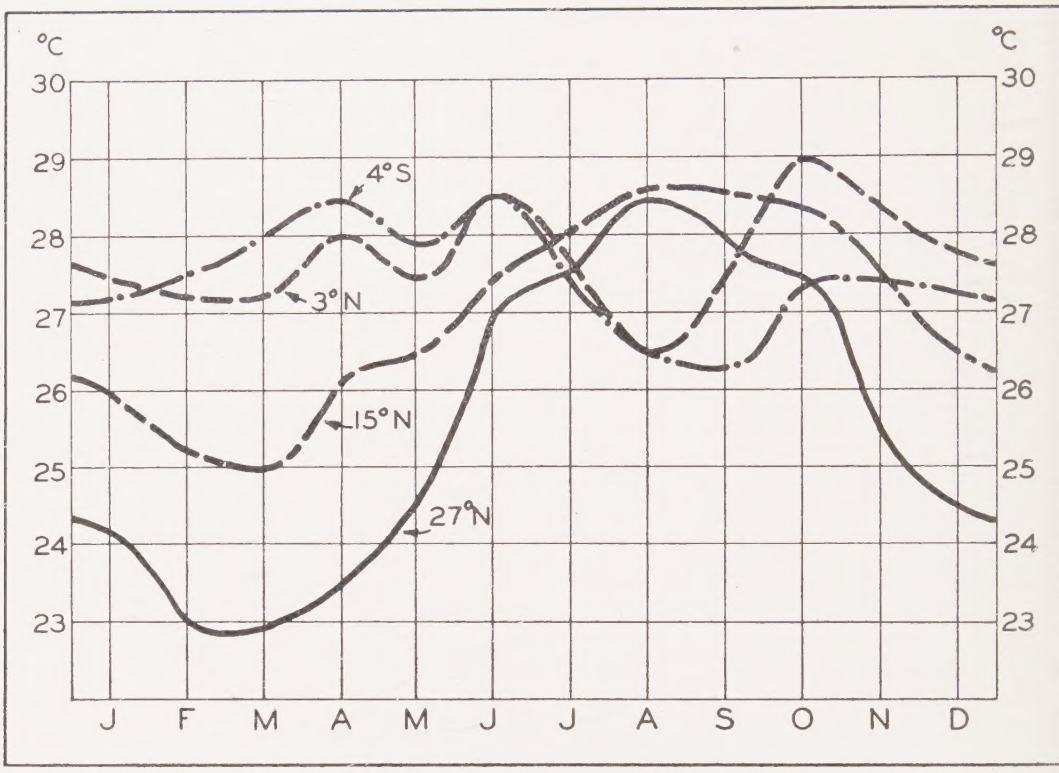


FIG. 6



AVERAGE ANNUAL MAXIMUM AND MINIMUM TEMPERATURES
NEW YORK – CAPE SÃO ROQUE

FIG. 7



YEARLY CYCLE OF TEMPERATURE AT VARIOUS LATITUDES

NEW YORK – CAPE SÃO ROQUE

FIG. 8